Quantifying Adaptability of Building Operations

Mohamed Ouf¹, William O'Brien², Burak Gunay², Afaf Azzouz³, Philip Richard³, Giuliano Todesco³

¹Concordia University, Montreal, QC Canada

²Carleton University, Ottawa, ON Canada

³Stantec Consulting, Ottawa, ON Canada

Abstract

The proliferation of building automation systems, smart and predictive control strategies can improve buildings' adaptability to occupancy variations. However, no holistic metrics currently exist to evaluate these technologies nor to quantify this aspect of building performance. To this end, we present a technology-neutral approach to define adaptability as a building performance attribute and propose metrics to quantify it. To demonstrate this approach, a case-study based on simulating a single-story office was used to compare several control strategies with regards to their effect on improving adaptability, especially under variable occupancy scenarios. The proposed metrics enable designers and operators to quickly evaluate the effect of different control strategies and design decisions on building adaptability.

1. Introduction

New societal trends such as teleworking, co-working, and home-sharing are rapidly changing building occupancy patterns. For example, more than half of the Canadian workforce reported having flexible work schedules which has implications on the time they spend in their homes and offices (Zeytinoglu et al. 2009). This trend will likely keep increasing, in part due technological advances that facilitate remote work and virtual communications. Standard assumptions suggest offices are nearly fully occupied on weekdays while residential dwellings are nearly fully occupied on weeknights and weekends (ASHRAE, 2016; National Research Council, 2015). In contrast, previous studies found that actual occupancy in office buildings rarely exceeds 50% on weekdays, with large variations from one space to another (Mahdavi et al. 2008; Yang and Becerik-Gerber, 2014a, 2014b).

Despite these findings, schedules (for occupancy and load profiles) used for simulation at the building design stage were largely developed in the 1980s (Abushakra et al. 2004) – before the concepts of telecommuting and virtual communications became commonplace. Furthermore, in existing buildings, operators typically respond to the diversity in occupancy patterns by choosing more conservative schedules - for example by reducing temperature setback periods to minimize potential occupant complaints (Gunay et al. 2015). This results in maintaining comfortable conditions for a longer period than occupancy duration, which increases energy use unnecessarily. The same issues also apply to other building systems such as lighting and ventilation, which are typically controlled under the assumption of full or

near full occupancy. However, it must be noted that the design of building systems and granularity of available controls can also prevent building operations from quickly responding to occupancy variations.

1.1 Defining building operations' adaptability

Within the context of this paper, "adaptability" refers to the degree to which building systems' operations and energy use is proportional to the number of occupants at both the temporal and spatial scales. Figure 1 shows a conceptual representation of optimal adaptability relative to traditional operational strategies that do not adjust building operations to variable occupancy. Adaptable operations arguably decrease energy use under lower occupancy conditions up to a certain limit, because reducing energy use in unoccupied buildings or spaces to zero is practically unfeasible – for several reasons such as mandatory safety and security requirements and maintaining temperature and humidity conditions to prevent potential damage.

Figure 1: Conceptual overview of adaptable building performance

Several building systems and controls can improve buildings' adaptability such as demand-controlled ventilation (DCV), occupancy-based lighting controls, and model predictive control strategies. These systems can achieve significant energy savings for different end-uses such as lighting, heating and cooling. For example, Brandemuehl and Braun (1999) showed up to 20% savings in electrical energy use for cooling in an office building because of using DCV. Other adaptable control strategies to control lighting, heating and cooling set-points were also found to achieve significant energy savings in previous studies (Gunay et al. 2015, Gunay et al. 2017a, 2017b; Henze et al. 2005; Ma et al. 2012;

Moroşan et al. 2010; Nagy et al. 2015; Peng et al. 2017). Woolley et al. (2014) argued that the energy savings of these systems are very sensitive to their responsiveness to occupancy variations. For example, the performance of model predictive controls is highly dependent on the accuracy and consistency of short-term predictions used to identify optimal control decisions (Gunay et al. 2014). Therefore, in addition to quantifying associated energy savings, evaluation of these systems should reflect the degree to which they improve buildings' adaptability to occupancy variations.

Building performance metrics are defined as any measurable quantity that assesses a performance attribute such as structural reliability, environmental impact, or energy efficiency. They should reflect progress towards achieving a specific goal with a clear definition of the boundaries of their measurement (Deru et al. 2005). The occupant-related domain is relatively under-developed with regards to building performance metrics, despite its significant effect (O'Brien et al. 2017). In other words, commonly used building performance metrics (e.g. energy use intensity) do not evaluate nor quantify adaptability at both the design and operational phases. Therefore, building energy codes and standards rely on prescriptive requirements to increase buildings' adaptability. For example, ASHRAE Standard 90.1 (2016) only requires DCV for spaces larger than 50 m² with a design occupancy greater than 25 people per 100 m². Similarly, occupancy-based lighting controls are only specified for certain building and space types - for example to automatically reduce lighting by at least 50% within 20 minutes of occupants' departure (ASHRAE, 2016). However, there is a growing trend towards performance-based code compliance using building simulations. This approach relies on specified schedules that assume repetitive and near-full occupancy. One of the disadvantages of these assumptions is downplaying the potential benefits of adaptable building technologies which are more significant under low and variable occupancy scenarios (O'Brien and Gunay, 2019).

1.2 Goals and Objectives

The main goal of this paper is to propose a new set of technology-neutral building performance metrics to evaluate building operations' adaptability.

The proposed metrics can be widely applied to assess the contribution of different building systems towards improving adaptability. They focus on evaluating different energy end-uses relative to occupancy patterns and reporting energy consumption normalized to hourly occupancy. They can be calculated from building performance simulation outputs or using data collected from building energy management systems (BEMS) in existing buildings. This paper will focus on providing detailed descriptions of the proposed metrics and their calculation methods. A simulation-based investigation of an office building will be used as an example to demonstrate the process of calculating these metrics and using them to evaluate control strategies.

Calculating some of the proposed metrics requires detailed occupancy data, which may not be available in existing or new buildings, especially for new buildings at the design stage. Therefore, alternative calculation methods and simulation approaches to represent variable occupancy are also presented. With the shift towards occupant-centric building design and operations, this paper's contributions are relevant for building energy codes and rating schemes as they provide widely applicable and reproducible metrics to evaluate adaptability - a typically overlooked aspect of building performance. Furthermore, the proposed metrics can be used to assess and compare different building technologies and control strategies.

2. Research Method: Developing adaptability metrics

The performance objective to be quantified using the proposed metrics is defined as "building operations' adaptability to variable occupancy". The conceptual framework used to categorize the proposed metrics resulted in three distinctive groups that measure different aspects of adaptability as follows:

1. Metrics focusing on quantifying occupied vs. unoccupied energy use
2. Metrics focusing on measuring the utilization of different building systems at full capacity relative to equivalent occupancy at full capacity
3. Metrics focusing on using occupancy as the normalizing factor for building performance reporting rather than floor area

The proposed metrics can be reported at annual, monthly or daily resolutions. They can also focus on specific building zones or entire buildings. If the goal is assessing overall building operations, adaptability metrics should be calculated at the building scale over annual periods. However, focusing on a certain building zones during parts of the year can provide useful insight. For example, calculating the unoccupied energy use ratio for a sparsely occupied zone at specific times of the year can provide a quick indication of non-adaptable performance and prompt operational changes to its mechanical or lighting systems.

Given the importance of data availability for calculating the proposed metrics, alternative calculation methods if detailed occupancy data is unavailable are discussed in this section. The following sub-sections provide more detailed explanation of the proposed metrics and their calculation approaches.

2.1 Unoccupied energy use

The first category of adaptability metrics focuses on energy use during occupied vs. unoccupied hours. These metrics quantify the amount of energy used while the building or zone is unoccupied. If accurate hourly occupancy data is unavailable, these metrics can be estimated based on projected occupancy patterns. For example, an overnight ratio can be used for office buildings where night-time occupancy is expected to be

zero. Selecting the exact timing of night hours for such analysis may vary from one building to another based on its type and any known information about its typical use.

The proposed unoccupied ratios can be calculated based on equations 1 – 5 for lights, plug loads, fans, heating and cooling, respectively. The time scale used for calculating these metrics can vary from a few days to a whole year depending on the analysis objective and available data. Similarly, these metrics can be calculated for an entire building or can focus on specific zones. A similar approach can be used to quantify the duration of maintaining heating/cooling set-points while a zone is unoccupied, relative to the total duration at which heating/cooling set-point is maintained. It must be noted that the type of mechanical systems used in the building and the HVAC zoning layout affects the possibility of calculating these metrics at the zone level. For example, if the building's mechanical system does not include terminal fans, fan energy use should be calculated for air handling units serving multiple zones.

$$\text{Unoccupied light use ratio} = \frac{\sum_{i=1}^n L_{\text{unoccupied}, i}}{\sum L_{\text{total}}} \quad (1)$$

$$\text{Unoccupied plug loads use ratio} = \frac{\sum_{i=1}^n P_{\text{unoccupied}, i}}{\sum P_{\text{total}}} \quad (2)$$

$$\text{Unoccupied fan use ratio} = \frac{\sum_{i=1}^n F_{\text{unoccupied}, i}}{\sum F_{\text{total}}} \quad (3)$$

$$\text{Unoccupied heating ratio} = \frac{\sum_{i=1}^n H_{\text{unoccupied}, i}}{\sum_{i=1}^n H_{\text{total}, i}} \quad (4)$$

$$\text{Unoccupied cooling ratio} = \frac{\sum_{i=1}^n C_{\text{unoccupied}, i}}{\sum_{i=1}^n C_{\text{total}, i}} \quad (5)$$

where n is the total number of zones in the building, $L_{\text{unoccupied}}$ is light use during unoccupied hours, L_{total} is total light use, $P_{\text{unoccupied}}$ is plug loads use during unoccupied hours, P_{total} is total plug loads use, $F_{\text{unoccupied}}$ is fan energy use during unoccupied hours, F_{total} is total fan energy use, $H_{\text{unoccupied}}$ is heating energy use during unoccupied hours, H_{total} is total heating energy use, $C_{\text{unoccupied}}$ is cooling energy use during unoccupied hours, C_{total} is total cooling energy use. *Note that these metrics can be calculated at different temporal and spatial scales*

A lower value for unoccupied ratio is more desirable for all end-uses since it indicates that less energy is used in the building when it is unoccupied. Theoretically, the minimum unoccupied energy use would be zero, but practical limitations due to safety and operational requirements mean that energy use is still needed even when the building is completely unoccupied. For example, some building systems such as thermally activated slabs must be operated prior to occupants' arrival due to their slow response. These considerations should be accounted for when evaluating unoccupied energy use ratios, yet the goal of building designers and operators should be minimizing unoccupied ratios to increase buildings' adaptability.

2.2 Utilization factors

The second category of adaptability metrics focuses on the utilization of different building systems. It is partially inspired by a common metric used in electrical engineering bearing the same name. It represents the ratio

of time a piece of equipment is in use relative to the total time at which it could have been in use (Bayliss and Hardy, 2012). In other words, this metric focuses on equipment use duration as a measure of its utilization. Within the context of buildings' adaptability, the proposed utilization factors were adapted to quantify the equivalent duration of energy use at full capacity relative to the equivalent duration of occupancy at full capacity.

Utilization factors can be calculated using equations 6 – 10 for lights, plug loads, fans, heating, and cooling, respectively. Although granular occupancy data is required to calculate these factors, the equivalent hours of occupancy at full capacity can also be estimated based on information about building use. Similar to unoccupied use ratios, the proposed utilization factors can be calculated at various temporal and spatial scales depending on available data and the analysis objective.

$$\text{Light utilization factor} = \frac{\sum_{i=1}^n \frac{L_i}{L_{\text{max}, i}}}{\sum_{i=1}^n \frac{O_i}{O_{\text{max}, i}}} \quad (6)$$

$$\text{Plug loads utilization factor} = \frac{\sum_{i=1}^n \frac{P_i}{P_{\text{max}, i}}}{\sum_{i=1}^n \frac{O_i}{O_{\text{max}, i}}} \quad (7)$$

$$\text{Fans utilization factor} = \frac{\sum_{i=1}^n \frac{F_i}{F_{\text{max}, i}}}{\sum_{i=1}^n \frac{O_i}{O_{\text{max}, i}}} \quad (8)$$

$$\text{Heating utilization factor} = \frac{\sum_{i=1}^n \frac{H_i}{H_{\text{max}, i}}}{\sum_{i=1}^n \frac{O_i}{O_{\text{max}, i}}} \quad (9)$$

$$\text{Cooling utilization factor} = \frac{\sum_{i=1}^n \frac{C_{\text{max}, i}}{C_{\text{max}, i}}}{\sum_{i=1}^n \frac{O_i}{O_{\text{max}, i}}} \quad (10)$$

Where L_i is the total hourly light use in zone i , $L_{\text{max}, i}$ is the design peak light use in zone i , O_i is the sum of occupant-hours in zone i , $O_{\text{max}, i}$ is the peak number of occupant-hours in zone i , P_i is the total hourly plug loads use in zone i , $P_{\text{max}, i}$ is the peak plug loads use in zone i , F_i is the total fan energy use in zone i , $F_{\text{max}, i}$ is the peak fan energy use in zone i , H_i is the total heating energy use in zone i , $H_{\text{max}, i}$ is the peak heating energy for zone i , C_i is the total cooling energy use in zone i , $C_{\text{max}, i}$ is the peak cooling energy for zone i

Although utilization factor is a unitless metric, a lower value indicates less energy is used relative to occupancy. A utilization factor of one means that building systems are used proportionally to the number of occupants (i.e. the equivalent duration of energy use at full capacity is equal to the equivalent duration of occupancy at full capacity). Therefore, a lower value for utilization factors is desirable since it indicates less energy is used relative to occupancy. In some cases, the utilization factor may be even lower than one if the equivalent duration of using building systems at full capacity is lower than the equivalent duration of occupancy at full capacity. This would result from building systems that adapt to external factors other than the number of occupants., such as daylight controls.

2.3 Occupant-normalized energy use

The proposed set of metrics in this category focus on normalizing energy use by the aggregate hourly number of occupants (i.e. occupant-hours), which implicitly accounts for occupancy variations. Calculating these metrics requires hourly occupancy data and can be done using equations 11 – 15 for lights, plug loads, and fans, heating and cooling respectively. These metrics can also be calculated at various temporal and spatial scales

depending on available data and the analysis objective similar to the previous categories.

$$\text{Occupant} - \text{normalized light use} = \frac{\sum_{i=1}^n L_i}{\sum_{i=1}^n O_i} \quad (11)$$

$$\text{Occupant} - \text{normalized plug loads use} = \frac{\sum_{i=1}^n P_i}{\sum_{i=1}^n O_i} \quad (12)$$

$$\text{Occupant} - \text{normalized fan use} = \frac{\sum F_{\text{total}}}{\sum O_{\text{total}}} \quad (13)$$

$$\text{Occupant} - \text{normalized heating energy use} = \frac{\sum F_{\text{total}}}{\sum O_{\text{total}}} \quad (14)$$

$$\text{Occupant} - \text{normalized cooling energy use} = \frac{\sum F_{\text{total}}}{\sum O_{\text{total}}} \quad (15)$$

where L_i is the total hourly light use in zone i , O_i is the total occupant-hours in zone i , P_i is the total hourly plug loads use in zone i , F_{total} is the total fan energy use in the building, and O_{total} is the total number of occupant-hours across the building.

A lower value for occupant-normalized energy use is desirable since it implies better adaptability. However, since many other factors affect energy use, this category of metrics may be influenced by other building-specific parameters such as the type of mechanical systems used or envelope characteristics. Despite these influences, normalizing energy use to the number of occupants rather than floor area under the same conditions (e.g. for the same building and under similar weather conditions) provides an indication for adaptability. Designers and operators should aim to decrease the value of occupant-normalized energy use to the lowest attainable levels to reflect improved adaptability.

2.4 Whole building metrics

Two approaches are presented in this paper to quantify overall building adaptability. The first focuses on quantifying average unoccupied ratios and utilization factors based on these calculated metrics for all end-uses. These averages represent the overall adaptability performance of different building systems and end-uses. An alternative approach, presented below, entails calculating the three categories of adaptability metrics using total energy use and overall building occupancy as shown in equations 16 – 18. If detailed occupancy data does not exist for the building, occupancy profiles may also be estimated based on available information regarding the building's typical use.

$$\text{Unoccupied total energy use ratio} = \frac{\sum E_{\text{unoccupied}}}{\sum E_{\text{total}}} \quad (16)$$

$$\text{Total energy utilization factor} = \sum \frac{E_{\text{total}}}{E_{\text{max}}} / \sum \frac{O_{\text{total}}}{O_{\text{max}}} \quad (17)$$

$$\text{Occupant} - \text{normalized total energy use} = \frac{\sum E_{\text{total}}}{\sum O_{\text{total}}} \quad (18)$$

where $E_{\text{unoccupied}}$ is the aggregate hourly energy use during unoccupied hours, E_{total} is the total energy use, E_{max} is peak energy use, O_{total} is the sum of occupant-hours in the building, and O_{max} is the peak number of occupant-hours.

This group of metrics is only applicable at the building level but may be calculated at different temporal scales. A benchmark or minimum threshold for these metrics would vary based on building type, location and other factors. However, a lower value is generally desirable as it indicates more adaptability.

3. Results: Case-study simulation to demonstrate using adaptability metrics

A case-study based on simulating a single-story office building, shown in Figure 2, is presented to demonstrate an example of using the proposed adaptability metrics. The building envelope specifications were chosen based on ASHRAE Standard 90.1's (2016) requirements for climate zone 6a, while its mechanical system was modeled as a dedicated outdoor air system. A central air handling unit (AHU) was modeled to supply outdoor air, with fan coil units in each zone for recirculation. All other inputs related to occupant density, lighting and equipment power density were specified per ASHRAE Standard 90.1 for office buildings.

Figure 2: Dimensions of the modeled office building

Results of an annual simulation of this building were used to calculate the proposed metrics, which are presented in Table 1. Based on the metrics definitions explained earlier, a lower value is generally more desirable as it implies higher adaptability. Unoccupied use ratios and utilization factors were lowest for cooling energy use because the building was simulated in a heating-dominated climate. Furthermore, the cooling availability schedule based on standard schedules assumes no overnight cooling for this climate. On the other hand, metrics related other end-uses, such as heating, lights and fans were relatively higher.

Table 1: Adaptability metrics of a single-story office building simulated in ASHRAE climate zone 6a

Metric	Unit	Value
Unoccupied use ratios		
Light use ratio	-	0.07
Plug loads use ratio	-	0.22
Fan use ratio	-	0.12
Heating ratio	-	0.46
Cooling ratio	-	0.01
Utilization factors		
Lights	-	1.39
Plug loads	-	1.96
Fans	-	1.12
Heating	-	0.14
Cooling	-	0.056

Occupant-normalized energy use

Light use	0.23
Plug loads use	0.36
Fan use	kWh/occupant- hour/year 0.1
Heating energy use	0.29
Cooling energy use	0.04

Whole building metrics

Average unoccupied - use ratio	0.098
Average utilization - factor	0.92
Unoccupied total - energy use ratio	0.15
Total energy utilization - factor	0.21

3.1 Using adaptability metrics to evaluate lighting control strategies

The proposed metrics were used to evaluate the effect of different lighting control strategies on improving adaptability. Some of the evaluated lighting control strategies included occupancy-based controls which required more precise information about each occupant's presence within the building. Therefore, individual occupants' presence was simulated using the Page et al. (2008) model, which is a stochastic agent-based model that treats occupants as individuals. The input schedule used for the Page et al. (2008) model was the ASHRAE Standard 90.1 office occupancy schedule multiplied by 0.8, 0.6, and 0.4, representing high, medium, and low occupancy, respectively.

This demonstration only focused on the west-facing perimeter zone of the building as an example since some of the implemented controls included daylight controls. For the proposed occupancy-based controls, light use in this zone was assumed to be proportional to the number of occupants present at each time step, where the total number of modelled occupants was four. In other words, 25% of the west zone's light use was controlled based on each occupant's presence profile (since it has a maximum occupancy of four). Four different lighting control strategies were investigated. The first strategy, which represented the baseline case for this analysis, entailed using ASHRAE Standard 90.1 lighting schedules for offices (i.e. schedule-based controls). The second strategy focused on occupancy-based controls where lights are automatically turned on as soon as the occupant arrived in the zone and turned off after 15 minutes from the occupant's departure. The third strategy included the same occupancy-based controls in addition to daylight controls with continuous dimming to maintain workplane illuminance at 500 lux. The fourth controls strategy used the same control logic for occupancy-based and daylight controls used in the third case, but without the 15-minute delay in switching lights off upon occupants' departure.

Figure 3 shows a visual comparison of annual light use under low occupancy conditions (ASHRAE 90.1 occupancy schedule multiplied by 0.4) given each of the investigated lighting control strategies. The goal of increasing adaptability is minimizing instances where lights are used in this zone while it is unoccupied.

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Figure 3: Light use relative to occupancy under low occupancy and a) schedule-based controls b) occupancy-based controls with a 15-minute delay, c) occupancy-based controls with a 15-minute delay and daylight controls, d) occupancy-based controls without vacancy delay and daylight controls

Light utilization factors were calculated under the different occupancy scenarios described above to quantify the effect of lighting control strategies on improving adaptability as shown in Figure 4. Results indicate that light utilization factor was lower for occupancy-based controls under all simulated occupancy scenarios (standard, high, medium, low). In contrast, light utilization factors generally increased at lower occupancy, which indicates lower adaptability as occupancy level decreases. One of the notable observations, however, is the slower rate of increase in utilization factors' value when occupancy-based controls were simulated. This observation highlights the advantages of these control strategies in maintaining adaptability as occupancy decreases. Similar observations were also found for occupant-normalized light use which decreased with occupancy-based controls for all occupancy levels.

Figure 4: Changes in lights utilization factor and occupant-normalized light energy use with different control strategies and occupancy scenarios

4. Discussion

A new approach to assess building performance was proposed by focusing on adaptability to variable occupancy. Previous studies suggest that building occupancy is typically lower than assumed, thus evaluating building performance under these conditions is necessary. Although technologies to adapt building operations and energy use to lower occupancy exist, the proposed metrics enable evaluating and comparing their effect on improving adaptability. Some of the proposed metrics have limitations since they may not capture all aspects of adaptability. For example, unoccupied ratios do not account for occupancy variations while the building is occupied. The proposed utilization factors address this issue by analyzing building energy use relative to variable occupancy, yet they can be relatively more challenging to calculate. Generally, the proposed metrics should be interpreted within the context of their potential limitations in quantifying adaptability, which should be addressed in future research.

One of the key requirements for evaluating adaptability is access to data regarding occupancy patterns. Although detailed occupancy data for different building zones is typically unavailable at the design phase, different approaches to represent occupancy variations can be used as shown in the presented case-study. However, stochastic models for predicting occupancy such as the one developed by Page et al. (2008) may not be universally applicable since they were developed using data collected in a small sample of buildings. Due to the uncertainty in predicting occupancy, a standardized approach is required for calculating the proposed metrics. One of the main suggestions for such approach would be conducting a sensitivity analysis considering three levels of occupancy (high, medium and low). Calculating adaptability metrics under each of these occupancy scenarios and reporting their average results can then be used to evaluate and

compare adaptability performance. Furthermore, a standardized reporting scheme can be developed, which would enable ranking buildings against each other with regards to their adaptability.

During the operational phase of a building, occupancy data may exist, yet its granularity and accuracy also varies widely. The proliferation of new technologies and occupant sensing infrastructure are key developments that enable collecting occupancy data at higher temporal and spatial resolutions (O'Brien et al. 2017). Haq et al. (2014) provided an overview of these technologies which range from PIR, to radio frequency identification (RFID) and wireless sensors, as well as image-based detection systems, since they facilitate collecting occupancy counts at fine resolutions. Other new approaches to collect occupancy data include detecting WiFi counts, or processing of surveillance camera feeds (Gunay et al. 2016). These advances enable more accurate representation of building occupancy, which can in-turn be used to calculate the proposed adaptability metrics.

Hourly energy use data is also required to calculate the proposed metrics in existing buildings. Therefore, the availability of sub-meters for energy end-uses in different building spaces is critical. Alternatively, the BEMS in existing buildings can be used to collect hourly end-use data for different building zones. These systems enable remote collection of granular data (Minoli et al. 2017), which can be used to calculate the proposed adaptability metrics. As a result of ASHRAE Standard 90.1's requirement for energy end-uses to be separately sub-metered at 15-minute intervals and archived for three years, the availability of granular energy use data is also expected increase. These developments can increase the potential for using the proposed adaptability metrics.

5. Conclusion

Current energy codes and standards only address adaptability through prescriptive requirements. Therefore, performance-based compliance with these codes and standards, which assume full or near full occupancy, may undermine the potential benefits of systems that increase building adaptability. This work proposed new building performance metrics that can be mandated by energy codes and standards to assess adaptability. Although this paper did not provide benchmarks for the proposed metrics, future work on this topic should focus on identifying adaptability benchmarks for different building types and climate zones and standardizing their calculation approach.

Introducing adaptability metrics provides an occupant-centric building performance evaluation approach, which rewards building technologies and control strategies that adapt to occupancy variations. Although previous studies showed the energy savings potential of these technologies, no metrics exist to quantify how well they adapt to partial occupancy. By providing reproducible and comparable metrics that fit the purpose of evaluating adaptability, building designers and operators can quickly evaluate the effect of different operational strategies and design decisions on this aspect of building performance.

However, one of the challenges of calculating the proposed metrics is the requirement for granular occupancy and energy use data, which may not be available. To address this issue, alternative calculation methods based on estimating occupancy profiles or performing sensitivity analyses were proposed. Future research should focus on standardizing building performance data collection and processing methods for calculating adaptability metrics to ensure their reproducibility.

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